Particle-species dependent modification of jet-induced correlations in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV

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We report PHENIX measurements of the correlation of a trigger hadron, at intermediate transverse momentum ($2.5 < p_{\mathrm{T,trig}} < 4$ GeV/c), with associated mesons or baryons, at lower $p_{\mathrm{T,assoc}}$, in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The jet correlations, for both baryons and mesons, show similar shape alterations as a function of centrality, characteristic of strong modification of the away-side jet. The ratio of jet-associated baryons to mesons for this jet, increases with centrality and $p_{\mathrm{T,assoc}}$ and, in the most central collisions, reaches a value similar to that for inclusive measurements. This trend is incompatible with in-vacuum fragmentation, but could be due to jet-like contributions from correlated soft partons which recombine upon hadronization.

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Recent measurements at the Relativistic Heavy Ion Collider (RHIC) have indicated the creation of a new state of matter in heavy-ion collisions [1]. The "soft" or small momentum transfer processes leading to the formation of this collision medium are sometimes accompanied by hard parton-parton scatterings. These scattered partons interact strongly with the medium and lose energy as they propagate through it, before fragmenting into jets [2, 3]. This can lead to strong modification of both the yield and the angular correlation patterns of jets [4, 5]. Therefore, the study of jets can provide invaluable insights into the properties of the new state of matter.

Parton energy loss in the nuclear collision medium [2, 3] has been associated with the observation that the single particle yields of mesons (M) are significantly suppressed in Au+Au collisions, when compared to the yields in p+p collisions scaled by the number of binary nucleon-nucleon collisions [6, 7]. This suppression factor is $R^{M}_{\rm AA} \sim 0.2$, for transverse momentum $p_{\rm T} \gtrsim 4$ GeV/c (in the absence of suppression, $R_{\rm AA} = 1.0$). In contrast to meson behavior, a general pattern of baryon (B) enhancement (for intermediate $p_{\rm T} \sim 2-5$ GeV/c) relative to mesons has been observed in central Au+Au collisions at RHIC [8, 9]. This is dramatized by a strikingly large proton to pion ratio which is about three times larger than in p+p collisions [1]. In fact, there is no suppression for baryons for $p_{\rm T} \sim 1.5-4$ GeV/c (i.e. ($R^{B}_{\rm AA} \sim 1.0$)) [10], compared to the very strong suppression for mesons.

Quark recombination [11, 12, 13] has been used to explain the enhancement of baryon emission in the intermediate $p_{\rm T}$ range. Such models also provide an explanation for the observed dependence of the elliptic flow on hadron species in terms of the "universal" elliptic flow of constituent quarks [14, 15]. By contrast, results from jet-induced hadron correlation measurements [16] rule out simple models which only take account of jet fragmentation and the recombination of thermal quarks in a flowing medium. The dichotomy between these two sets of observations is currently an unresolved issue at RHIC.

Full suppression of the away-side jet in Au+Au collisions has been reported [17]. Recently, relative azimuthal angle ($\Delta\phi$) correlation measurements of the away-side jet partner hadrons at lower momentum have been found to be significantly modified [4, 5]. Indeed, these distributions show local minima at $\Delta\phi = \pi$ which contrasts with the characteristic jet peak observed in $p+p$ collisions. This modification has been linked to strong parton-medium interactions [5, 18].

A crucial question is whether or not such interactions could also induce correlations between soft partons (comprising the medium) which could then recombine to form jet-like fragments. To this end, we use measurements of $\Delta\phi$ correlation functions to make detailed investigations of the distributions and conditional yields of jet associated baryons and mesons. The study is made as a function of collision centrality and partner $p_{\rm T}$, for the trigger hadron selection $2.5 < p_{\rm T,trig} < 4.0$ GeV/c.

The hadron yield from jet fragmentation is relatively small in the intermediate $p_{\rm T}$ range, and recombination of uncorrelated soft partons cannot produce jet-like correlations. Thus, very little away-side jet correlation might be expected for associated baryons and mesons. By contrast, it has been argued [19] that energy loss, by a hard scattered parton propagating through the collision medium, can induce two-body correlations between soft partons in a region surrounding the hard parton's trajectory [20]. Soft partons from this region could then recombine into hadrons which not only correlate with each other, but also with the direction of the hard scattered parton. The process of recombination would also amplify these jet-like correlations for baryon creation compared to that for mesons and hence, result in particle ratios different from the in-vacuum fragmentation values.

Au+Au data (at $\sqrt{s_{NN}}$=200 GeV) was recorded during 2004 with the PHENIX detector [21]. Collision centrality was determined with the beam-beam counters (BBC) and zero degree calorimeters [21]. Charged particle tracking, identification, and momentum reconstruction in the central rapidity region ($|\eta| \leq 0.35$) was provided by two drift chambers, each with an azimuthal coverage $\Delta\varphi = \pi/2$, and two layers of multi-wire proportional chambers with pad readout (PC1 and PC3). To reject most background from albedo, conversions, and decays, a confirming hit was required within a 2σ matching window in PC3 [6].

Charged particles were identified via time-of-flight measurement with the time-of-flight (TOF) and lead scintillator (PbSc) detectors. The TOF covers $\Delta\varphi = \pi/4$ with good timing resolution $\simeq 120$ ps (see Ref. [16, 22]; the PbSc as used here, covers a larger solid angle ($\Delta\varphi = 3\pi/4$) with a modest timing resolution of 400 ps. The time-of-flight measurements were used in conjunction with the measured momentum and flight-path length, to generate a mass-squared (m^2) distribution [23] for charged particle identification. A cut about the baryon $(\bar{p}, p)$ peak in the m^2 distribution was used to distinguish baryons and mesons ($\pi^{\pm}, K^{\pm}$). The kaon contamination of the baryon sample is $\lesssim 3\%$ for the highest associated $p_{\rm T}$ bin used ($1.6 < p^{M,B}_{\rm T,assoc} < 2$ GeV/c). We generated area normalized two-particle correlation functions, in relative azimuthal angle $C\,(\Delta\phi)$, as the ratio of a foreground distribution $N_{\rm cor}(\Delta\phi)$, constructed with correlated particle pairs from the same event, and a background distribution $N_{\rm mix}(\Delta\phi)$, for pairs obtained by mixing particles

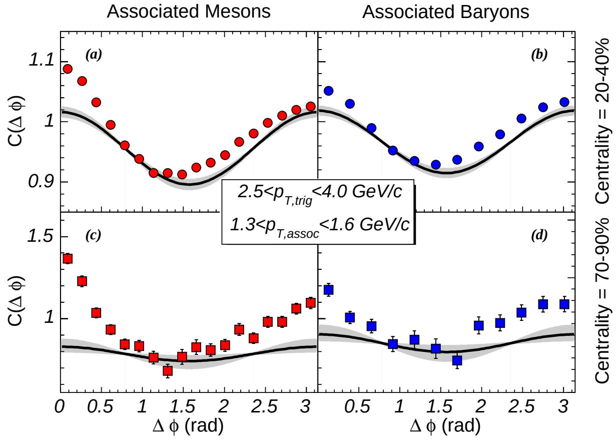

FIG. 1: (Color online) Correlation functions for associated partner mesons (a) and (c) and baryons (b) and (d) ($1.3 < p_{\mathrm{T}} < 1.6$ GeV/c) per trigger hadron ($2.5 < p_{\mathrm{T}} < 4.0$ GeV/c), for centrality selections of 20-40% (top panels) and 70-90% (bottom panels). The curves indicate elliptic flow contributions (see text).

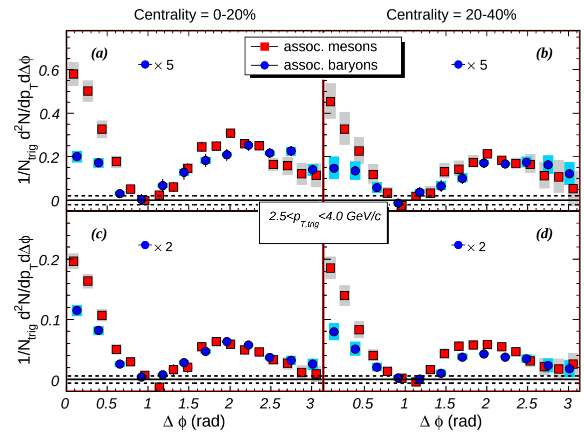

FIG. 2: (Color online) Jet-pair distributions for associated mesons (squares) and baryons (circles) for $1 < p_{\mathrm{T,assoc}} < 1.3$ GeV/c (top panels) and ($1.6 < p_{\mathrm{T,assoc}} < 2.0$ (bottom panels). Results are for a hadron trigger ($2.5 < p_{\mathrm{T}} < 4.0$ GeV/c) and centrality selections of 0-20% and 20-40%.

from different events having similar collision vertex and centrality [4, 24];

$$C\left(\Delta\phi\right) = \frac{N_{\mathrm{cor}}\left(\Delta\phi\right)}{N_{\mathrm{mix}}\left(\Delta\phi\right)} \frac{\int d\Delta\phi N_{\mathrm{mix}}(\Delta\phi)}{\int d\Delta\phi N_{\mathrm{cor}}(\Delta\phi)}. \qquad (1)$$

Representative examples of the correlation functions, so obtained for associated mesons and baryons ($1.3 < p^{M,B}_{\mathrm{T,assoc}} < 1.6$ GeV/c) per trigger hadron ($2.5 < p_{\mathrm{T,trig}} < 4.0$ GeV/c), are shown for two centrality selections in Fig 1. They indicate an asymmetry characteristic of (di)jet pair correlations (J($\Delta\phi$)) and an anisotropy signaling elliptic flow ($H(\Delta\phi) = 1 + 2(v_2^{\mathrm{trig}} \times v_2^{B,M})cos(2\Delta\phi)$) with amplitude $v_2^{\mathrm{trig}} \times v_2^{M,B}$ [4]; The observed correlation functions for associated partner mesons are more asymmetric than those for associated partner baryons, indicating that the jet signal is stronger for hadron-meson correlations. However, clear separation of the jet and flow correlations is required for further study.

Reliable extraction of J($\Delta\phi$) from $C(\Delta\phi)$ can be achieved if the normalization b$_o$, and $v_2^{\mathrm{trig}} \times v_2^{B,M}$ is known [24]. Values for v_2^{trig} and $v_2^{M,B}$ were obtained via measurements of the single particle distributions relative to the reaction plane, determined in the BBC's [14, 15]. The large (pseudo)rapidity separation ($\Delta\left|\eta\right| > 2.75$), between each BBC and the PHENIX central arms, minimizes any non-flow contributions to these v_2 values [25].

To fix the value of b$_o$ we followed the procedure in Refs. [4, 24] and assumed that J($\Delta\phi$) has zero yield at some minimum $\Delta\phi_{\mathrm{min}}$ (ZYAM). That is, the elliptic flow contributions are required to coincide with C($\Delta\phi$) at $\Delta\phi_{\mathrm{min}}$. Good precision for $\Delta\phi_{\mathrm{min}}$ was achieved via a fit to the correlation function; the systematic error on the magnitude of the integrated jet-function J($\Delta\phi$), due to the ZYAM procedure is estimated to be $\lesssim 3\%$. The solid lines in Fig. 1 show examples of the ZYAM normalized elliptic flow (v_2) contributions. The gray bands represent systematic errors on the v_2 amplitudes ($\sim 6\%$ for central and mid-central events, and $\sim 40\%$ for peripheral events.) primarily due to an uncertainty in the reaction plane resolution [4].

The associated meson and baryon jet distributions $\frac{1}{N_{\mathrm{trig}}}\frac{d^2N}{dp_{\mathrm{T}}d\Delta\phi}$ are shown in Fig. 2 for two associated p_{T} bins and for the centralities 0-20% and 20-40%. The shaded error bars indicate the systematic error related to v_2 subtraction. The associated baryon jet pair distributions are multiplied by the indicated factors to facilitate a shape comparison with the distributions for mesons.

Figure 2 shows that the correlation strength of the near side jet ($\Delta\phi \leq \Delta\phi_{\mathrm{min}}$, NS) is substantially weaker for associated baryons. In contrast, the shapes of the away-side jet distributions ($\Delta\phi \geq \Delta\phi_{\mathrm{min}}$, AS) are qualitatively similar for associated mesons and baryons. For the central and mid-central collisions shown, these distributions are also broad and decidedly non-Gaussian, with evidence for local minima at $\Delta\phi = \pi$ [4]. They provide confirmation that the topological signatures for strong jet modification are reflected in the jet pair distributions for both associated baryons and mesons [26]. The latter finding for baryons and mesons is an important constraint for models of strong jet-modification [12, 27, 28, 29].

The integral of the extracted J($\Delta\phi$) distribution is the fraction of particle pairs associated with the jet, i.e., the jet pair fraction (JPF); $JPF_{NS,AS} =$

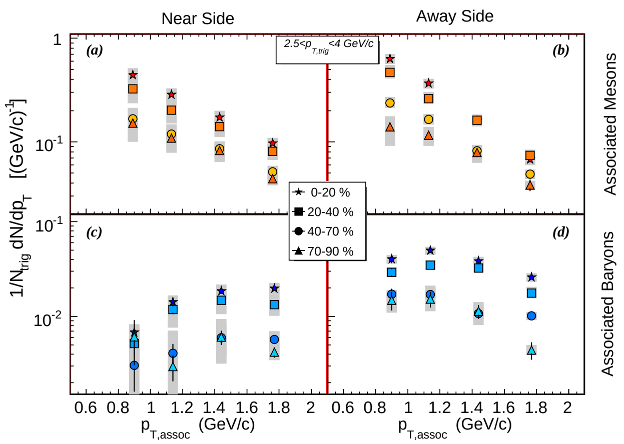

FIG. 3: (Color online) conditional jet yields for associated mesons (top panels) and baryons (bottom panels) for near- (left panels) and away-side (right panels) jets, as a function of associated particle p_T and collision centrality.

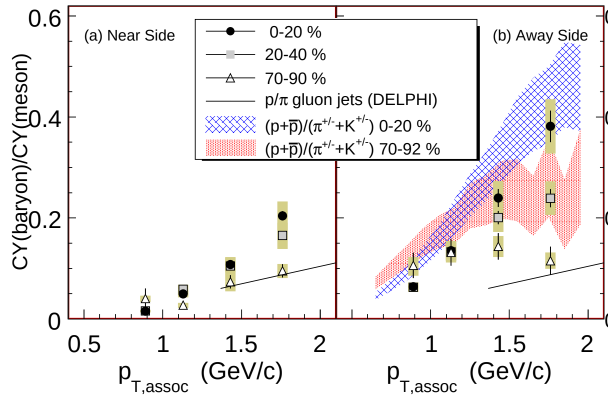

FIG. 4: (Color online) Ratio of jet associated baryons to jet associated mesons vs. $p_{\rm T,assoc}$ for the 0-20%, 20-40% and 70-90% most central collisions. The hatched bands indicate inclusive B/M ratios (see text).

$\sum_{i\in NS,AS} J(\Delta\phi_i)/\sum_i C(\Delta\phi_i)$ [24]. We use it to determine the conditional yield $\langle N^{M,B}\rangle/\langle N_{\rm trig}\rangle$, or efficiency corrected pairs per trigger [24];

$$\frac{\langle N^{M,B}\rangle}{\langle N_{\rm trig}\rangle} = JPF \times \frac{\langle N_d^{M,B}\rangle}{\langle N_s^{\rm trig}\rangle \times \langle N_s^{M,B}\rangle} \times \langle N_{eff}^{M,B}\rangle, \quad (2)$$

where $\langle N_d^{M,B}\rangle$ is the average number of detected hadron-meson(baryon) pairs per event, $\langle N_s^{\rm trig}\rangle$ and $\langle N_s^{M,B}\rangle$ are the detected singles rates for hadrons, and mesons and baryons respectively, and $\langle N_{eff}^{M,B}\rangle$ are the efficiency corrected singles rates. The systematic error associated with the latter is $\sim 10\%$. A further division by the p_T bin width gives the conditional yield $CY = \frac{1}{N_{\rm trig}}\frac{dN}{dp_T}$.

The conditional yields, for near- and away-side jet-associated mesons and baryons, are shown as a function of $p_{\rm T,assoc}^{M,B}$ and collision centrality in Fig. 3. The yields for associated mesons (Figs. 3 (a,b)) indicate an essentially exponential decrease with increasing $p_{\rm T,assoc}^{M}$, for both the near- and away-side jets. A decrease in the slope parameter ("temperature increase"), from peripheral to central collisions, is also apparent. For a fixed $p_{\rm T,assoc}^{M}$, these yields also show an increase from peripheral to central events, albeit with a stronger dependence for the away-side jet. This trend is incompatible with in-vacuum fragmentation, but could be due to jet-like contributions from correlated soft partons which recombine upon hadronization [19, 20].

The conditional yields for associated baryons differ strongly from those for associated mesons (cf. Figs. 3 (c,d)). That is, they do not show an exponential dependence on p_T^B over the measured range, and the yields for the away-side jet are substantially larger than those for the near-side jet. Interestingly, hadron-baryon pairs are disfavored in the same-side jet, relative to the away-side jet. A similar observation has been reported for charge selected (pp and $\bar{p}\bar{p}$) jet correlations [22].

For a given $p_{\rm T,assoc}^{B}$, the near- and away-side conditional yields increase as the collisions become more central, i.e., this trend is similar to that for the associated mesons. However, the baryon yields show a much stronger increase with centrality [26], as might be expected if correlated soft partons recombine and contribute to the away-side jet correlations [20].

The ratio of jet-associated baryons to jet-associated mesons is shown as a function of associated particle p_T in Fig. 4; the left and right panels show the ratios for the near- and away-side jets respectively, for three centrality selections as indicated. These ratios clearly increase with p_T, and with centrality for $p_T \gtrsim 1.4$ GeV/c. For peripheral collisions, the near side ratios compare well to the p/π ratio, for jets produced in $e^+ + e^-$ collisions (line) [30]. For more central collisions, the near- and away-side ratios are much larger, suggesting that the medium influences the relative composition of the associated particles.

The hatched bands in Fig. 4(b), show the inclusive B/M ratios (uncorrected for baryon and meson feed-down) as a function of p_T for the 0-20% and 70-92% most central Au+Au collisions [23]; an estimate of these ratios, after feed-down corrections, is within the systematic errors indicated by the bands. These ratios indicate that the trend of the centrality dependent baryon enhancement, apparent in the jet-associated conditional yields, is similar to that observed for the inclusive particle yields. They suggest that the underlying mechanism for baryon enhancement in both the inclusive and the current away-side jet measurements, have a common origin. Since recombination models can explain the enhancement of inclusive baryon yields, a qualitative explanation is that the away-side jet-like correlations result from the recombination of correlated soft partons induced via strong

parton-medium interactions.

In summary, we have measured per-trigger yield distributions for jet-associated mesons and baryons over a wide range of centrality and p_{T} in Au+Au collisions. The distributions for both species show similar shape modifications for the away-side jet, compatible with several jet modification models [12, 27, 28, 29]. The conditional yield distributions for mesons and baryons show different dependencies on collision centrality and associated particle p_{T}. The ratio of jet-associated baryons to mesons increases with centrality and p_{T}, similar to the data for inclusive measurements. These results can be qualitatively understood in terms of parton-medium interactions which induce correlations between soft partons, followed by recombination at hadronization [19, 20]. Future quantitative model comparisons are required to fully validate this mechanistic scenario. However, the current measurements offer important new insight that may reconcile the dichotomous observations that a simple quark recombination ansatz does not account for jet-induced hadron correlation measurements, but can explain the enhancement of baryon emission and the "universal" elliptic flow of hadrons at intermediate p_{T}.

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